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TECHNICAL PAPER to be presented at the
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ABSTRACT

A 1 kW Solar Array and Capacitor-Diode Voltage Multiplier Converter (S/A-CDVM) has been successfully integrated with a 30 cm-diameter mercury ion thruster system to provide ion beam power. Measurements were made to compare steady state and transient response performance of a conventional bridge converter with the S/A-CDVM converter used for the ion beam supply. The ability to recover from screen to accelerator arcs and promptly re-establish stable thruster performance was demonstrated. Solar array transient response to thruster arcing was measured.

INTRODUCTION

In space flight applications of primary electric propulsion the thrust system mass and efficiency are important considerations. For some planetary missions thruster system mass and efficiency are critical considerations in determining the feasiability for accomplishing the mission. The power processors constitute a major portion of the thrust system mass. Its efficiency determines the total solar array power requirement and thermal control mass required. These factors have driven the technology program for lightweight, efficient power processors.

A power processor which incorporates the capacitor-diode voltage multiplier (CDVM) concept (refs. 1 to 4) holds promise of fulfilling this need. A CDVM transfers energy from its source to the load by capacitance rather than magnetic coupling, and consequently does not require the weight intensive power transformer (and some of the inductors) used in series resonant and conventional converters. The CDVM converter allows the use of a higher switching frequency which reduces the circuit capacitance and filter inductance. By eliminating the transformer, using a high switching frequency, and incorporating high energy density capacitors, the mass and dissapative losses of the CDVM converter are significantly reduced over present day power processors. The efficiency of this type of converter has been demonstrated to be typically 95 percent (ref. 4).

The results of a recent study (ref. 5) of a space mission requiring an extended performance electric propulsion system (Comet Halley rendezvous) show that an 11 percent savings in thrust system

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mass and a 1.2 percent gain in overall thrust system efficiency can be achieved by using an unregulated CDVM converter for the screen supply in place of a regulated series inverter supply.

A 1 kW unregulated CDVM converter breadboard was fabricated as part of this study. This power level could easily be extended to 6 kW with reasonable confidence.

The CDVM converter has been integrated with a 30 cm-diameter mercury ion thruster system and an unregulated solar array. This paper documents the performance of the system. The thruster system performance was evaluated at beam currents of 0.6, 0.7, 0.86, and 0.9 ampere. The results are compared with a conventional bridge converter. Additionally, the ability to recover from screen to accelerator arcs and maintain performance was demonstrated, and the solar array transinet response during arcing was measured.

APPARATUS

The electrical system block diagram is shown in figure 1. The conventional power processor provides the 12 outputs (high voltage and low voltage groups shown) required to operate a 30 cm-diameter, electron bombardment, mercury ion thruster. The screen supply of the conventional power processor is routed through the interconnection console which provides switching of the screen voltage between the bridge and (S/A-CDVM) converter.

Thruster

A 30 cm-diameter electron-bombardment mercury ion thruster (SN 501) was used for this test. The thruster was originally a 400 series thruster built by Hughes Research Laboratories and modified by Lewis to be equivalent to a 700 series Engineering Model Thruster (EMT) described in reference 7.

Conventional Power Processing Console

The power processing console was designed and fabricated by Hughes Research Laboratories under contract NAS3-14104 (ref. 8). The control logic has been modified (ref. 9) to provide thruster control for a variety of potential near earth orbital and planetary missions (refs. 10 to 12). The closed-loop control was modified (ref. 13) to insure stable steady-state operation over the anticipated thermal environment of these potential missions.

The power supplies were 10 kHz, transistor switched, bridge inverters with output characteristics similar to flight-type hardware.

Solar Arrays

The solar array facility used in this experiment (described in ref. 14) consists of nine independent modules, each of which contains an array of 2560 polar cells (2 by 2 cm), a tungsten-iodide lamp bank, an infrared filter, and water and air cooling for the cells and lamps, respectively. Each module array contains two subpanels of 40 series strings, 32 solar cells long. Figure 2 shows one of the modules opened to display the solar array and its lamp bank. Each module can be wired to produce approximately 120 watts at voltages from 12 volts to 12 kilovolts. The nine modules were connected in parallel to have the V-I characteristic shown in figure 3. Open circuit voltage was 280 volts with the maximum power point occurring at 245 volts and 4.3 ampere.

CDVM Converter

The 1 kW unregulated CDVM converter circuit used in this investigation was designed and fabricated by Hughes Aircraft Co. under contract NAS3-20395 (ref. 15). The design emphasized high frequency (70 kHz) and an interconnected multiphase capacitor-diode network to achieve an efficiency of 95±0.3 percent from half to full power at a low line input of 200 volts. The specific component mass was 0.55 kg/kW. Figure 4 illustrates the five phase CDVM circuit and the voltage transfer ratio. The predicted and measured efficiencies for various input voltages and output load currents are shown in figure 5.

Facility

All tests were conducted in a 1.2 m-diameter bell jar on a 1.6 m-diameter by 21.4 m-long vacuum facility (ref. 15). The thruster was extended into the main chamber of the tank approximately 1 m beyond the tank wall during thruster operation to minimize ion beam-facility interactions. Bell jar pressure was typically 5×10^{-5} torr and main tank pressure 5×10^{-6} torr during thruster operation.

EXPERIMENTAL PROCEDURE

Two types of power processor/ion thruster performance were investigated. Steady state performance was documented. Oscillograms were taken of selected thruster parameters during both conventional converter and S/A-CDVM converter operation. Transient response performance was measured during high voltage screen to accelerator arcs. Oscillograms of the solar array input voltage and current were recorded to document conducted EMI.

Steady-State Performance - Conventional Bridge Converter

With the ion thruster in the vacuum chamber ($p < 5\times10^{-6}$ torr), power was applied from the conventional power processor. A startup routine similar to the one described in reference 17 was followed to achieve a desired closed-loop controlled operating condition (see table I). This operating condition was maintained for a minimum of 2 hours to insure thermal equilibrium before any performance data was taken.

Steady-state performance was documented and oscillograms of screen voltage (V_I), beam current (J_B), discharge voltage (ΔV_I), and discharge current (J_E) were recorded.

Steady-State Performance - S/A-CDVM Converter

With the ion thruster operating at the steady-state condition, the solar array facility was activated and the CDVM converter was turned on to provide screen voltage to the switching console. The closed-loop control of the vaporizers was momentarily placed into manual control and the screen supply was rapidly switched from the conventional converter to the S/A-CDVM converter and closed-loop control was re-established at the same beam current operating point. This condition was maintained for at least 30 minutes before any data was recorded.

Transient Response

With the power processor in the S/A-CDVM converter configuration, the screen and accelerator supplies were momentarily shorted to simulate an arc transient. This was done to ascertain high voltage recycle capability and record the CDVM converter input voltage and current excursions at the solar array interface.

The power processor was returned to the conventional converter configuration and the procedure was repeated for another beam current operating condition

RESULTS AND DISCUSSION

Steady-State Performance

Power processor-ion thruster performance measurements were made for beam currents of 0.6, 0.7, 0.8, 0.86, and 0.9 ampere. The operating parameters are given in table I and ion thruster performance data are compared in table II. The performance was found to be independent of the type of screen supply converter.

The 30 cm-diameter ion thruster operated in a stable and predictable manner over a beam power range of 688 to 1000 watts for the given beam currents. The differences in the comparative values of beam power (and other performance parameters shown in table II) result from the variation of unregulated S/A-CDVM output while the conventional converter provided a regulated output of 1125 volts. The beam current of 0.86 ampere was chosen as an operating point because the maximum power point of the S/A-CDVM (980 watts) occurs at this value. See figure 6 for the V-I output characteristic curve. No performance anomalie or operating difficulties was evidenced at the maximum power operating point.

Comparisons were made of the discharge and screen supply waveforms for the above currents. Figures 7 and 8 represent the typical screen voltage and current excursions for beam currents of 0.6 and 0.8 ampere, respectively. It was found that the screen current ripple was not affected by the type of converter used however the screen ripple voltage did change. Similar to the findings of other experiments (refs. 18 and 19), the discharge current fluctuations were found to directly contribute to the beam current fluctuations. The peak-to-peak screen voltage ripple decreased from approximately 150 volts for the bridge inverter to 60 volts for the CDVM. The difference is attributed to the higher switching frequency of the CDVM (70 kHz is compared to 10 kHz for the conventional converter) and output filter characteristics. Comparison of the discharge supply output waveforms reveal negligible differences for either type of converter.

Of particular concern in any spacecraft photovoltaic system is the conducted electromagnetic interference imposed onto the solar array bus by loads such as power processors. Measurements of the steady-state voltage and current ripple at the CDVM input are shown in figure 9 for beam currents of 0.7 and 0.9 ampere. The maximum voltage ripple was found to be about ±4 percent at a beam current of 0.7 ampere and the solar array current ripple was typically ±1 percent throughout the power range. This ripple resulted from the multiphase design and an input filter choke of 10 μh per phase.

Transient Response Performance

The most common perturbation to stable thruster operation is a high voltage arc break over. When this occurs, the high voltages must be momentarily turned off to extinguish the arc, the discharge current reduced to lower the plasma density, then high voltage is reapplied and the discharge current is ramped to its steady-state value to re-establish stable thruster operation (ref. 10).

Since the CDVM was powered from the solar array and an overload of the array would reduce the CDVM output voltage, it was decided to test the recycle capability without interconnecting the recycle control logic from the power processor. The power processor control logic governed the recycle operation of the accelerator and discharge supplies but not the S/A-CDVM converter. Arc overloads were caused by momentarily shorting the screen and accelerator connections at the vacuum feed through flange. The S/A-CDVM-ion thruster recycled and re-established steady-state performance each time an arc was struck.

Rapid load perturbations such as screen to accelerator arcs, are generally reflected to the converter input and can cause severe transients to be imposed onto the solar array bus. The transient response of the solar array to these perturbations is shown in figure 10. The solar array voltage momentarily decreased about 20 percent while the current reversed, increased to about 3 times the forward current and returned to zero in about 150 microseconds. The reversed current results from an energy imbalance between the decreasing solar array and input capacitors of the 5 phase capacitor-diode network. It should be noted that the objective of the breadboard design was to evaluate the CDVM concept at a power level that could easily be extended to 6 kW. No attention was given to transient control.

CONCLUSIONS

A 1 kW solar array and capacitor-diode voltage multiplier converter have been successfully integrated with a 30-cm-diameter mercury ion thruster system. Performance measurements were made to compare steady-state and transient response performance of a conventional bridge and a S/A-CDVM converter used for the screen supply.

No significant difference was found in performance comparisons of beam power, thrust propellent utilization, and specific impulse. The ion thruster performance was found to be independent of the type of screen supply converter.

The design of a multiphase capacitor-diode input network and the use of a high switching frequency (70 kHz) significantly reduced the input filter requirements to achieve reasonable ripple values on the solar array bus. Additionally the output filter requirements were reduced. The CDVM output voltage ripple was typically 3 times less than the conventional bridge converter output.

Transient response to arc overloads was measured. The S/A-CDVM ion thruster demonstrated the ability of recycle and re-establish steady-state performance in a normal manner for every overcurrent arc imposed on the thruster.

The conducted EMI imposed on the solar array bus during an overcurrent arc was also measured. The solar array voltage momentarily decreased about 20 percent while the current reversed, increased to about 3 times the forward current and returned to zero in about 150 microseconds.

Though the voltage multiplier converter concept has demonstrated the ability to successfully operate into a plasma load of a 30 cm ion thruster at the kilowatt level, its benefit as a spacecraft converter at the multikilowatt level would be derived from its weight savings. Because of the reduced magnetics requirement, higher frequency, and packaging of the capacitor-diode network, study results (ref. 5) have projected a packaged weight of 1.6 kgm/kW at 6 kW.

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TABLE I. - 30 CM-DIAMETER ION THRUSTER OPERATING PARAMETERS

	Beam current, amp				
	0.6	0.7	0.8	0.86	0.9
Screen voltage					
Conventional converter, V	1125	1125	1125	1125	1125
CDVM converter, V	1260	1220	1180	1140	1080
Accelerator voltage, V	-500	-500	-500	-500	-500
Accelerator current - MA	1.4	1.4	1.6	1.7	1.7
Discharge voltage, V	35.0	35.0	35.0	35.0	35.0
Emission current, A	3.42	4.00	4.58	4.90	5.33
Cathode keeper voltage, V	8.3	7.7	7.3	7.7	7.6
Cathode keeper current, A	.850	.882	.892	.916	.858
Neutralizer keeper voltage, V	13.5	13.5	13.6	13.6	13.7
Neutralizer keeper current, A	1.81	1.81	1.81	1.81	1.82
Coupling voltage, V	-9.81	-10.1	-10.3	-11.0	-12.4

TABLE II. - 30 CM-DIAMETER ION THRUSTER PERFORMANCE DATA

[Discharge loss, 200 eV/ion.]

Parameter		Beam - current, amp				
		0.6	0.7	0.8	0.86	0.9
Beam power, P_o, w	Conventional Conv.	688	805	920	1000	
	CDVM	769	854	944	980	972
[a]Thrust, T, mlb	Conventional Conv.	9.3	10.9	12.4	13.4	
	CDVM	9.8	11.3	13.7	14.0	13.7
Prop. utilization efficiency, η_u	Conventional Conv.	.601	.701	.770	.756	
	CDVM	.616	.701	.770	.756	
[a]Specific impulse, sec	Conventional Conv.	2041	2379	2613	2563	
	CDVM	2092	2526	2719		2596

[a]Parameter is ideal, no corrections for beam divergence or doubly ionized mercury H_g^{++}

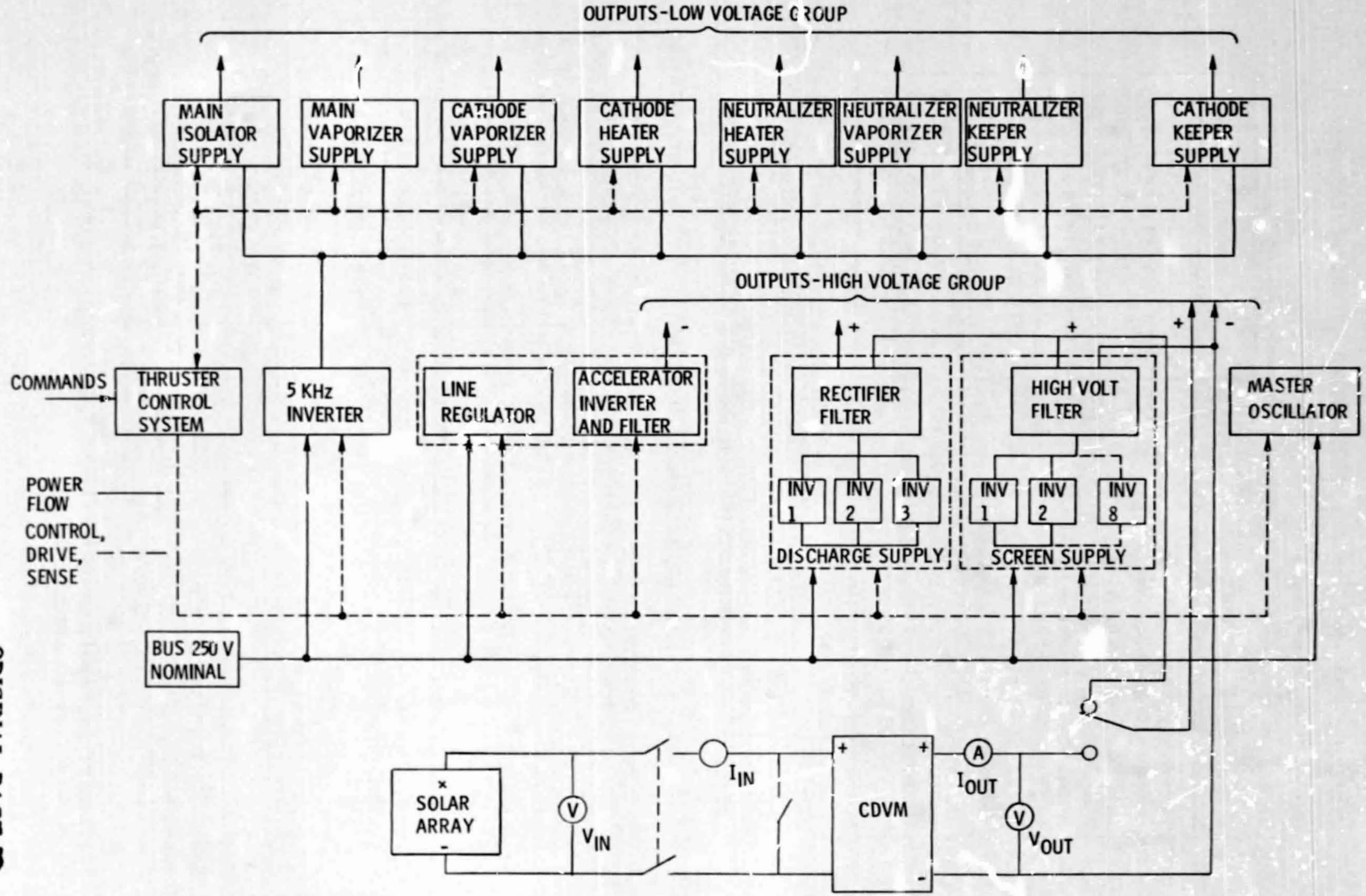

Figure 1. - Electrical system block diagram.

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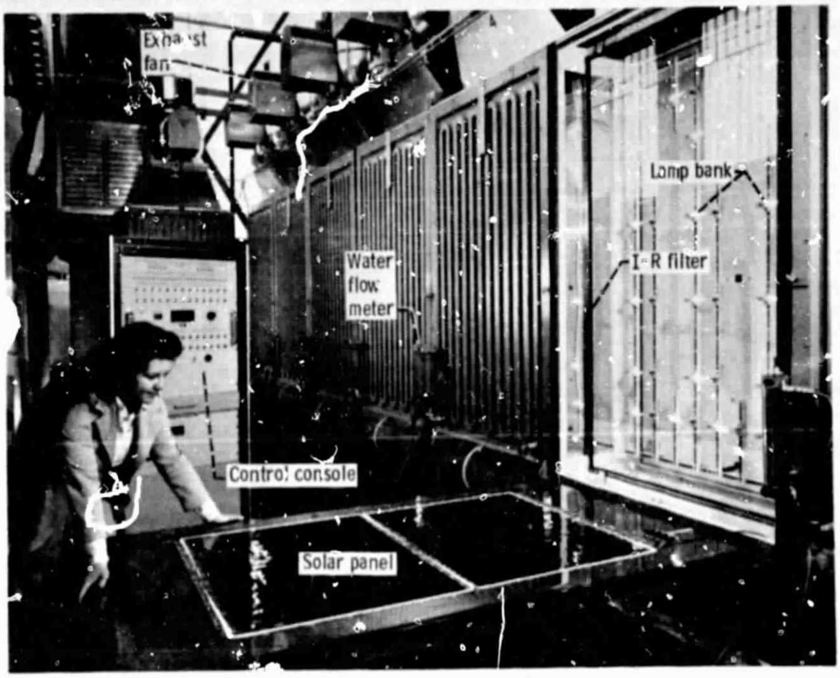


Figure 2. - 1-Kilowatt laboratory solar array facility with one of the nine modules opened to display array panel and lamp bank.

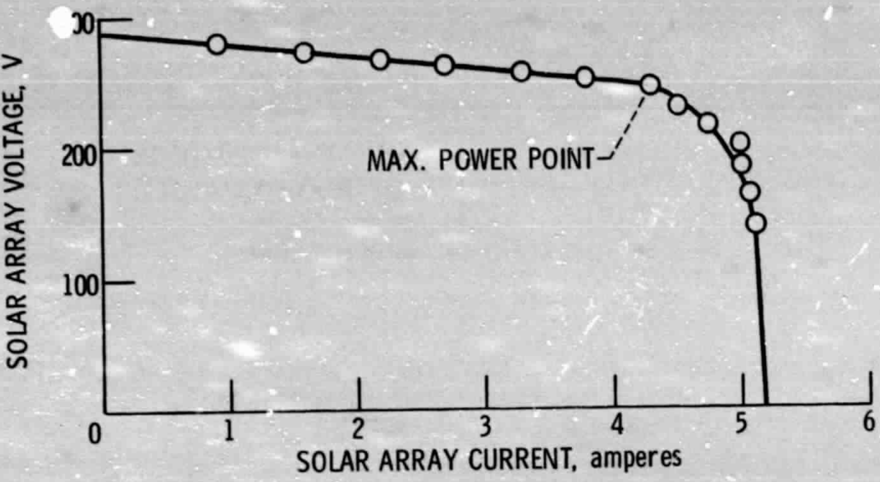
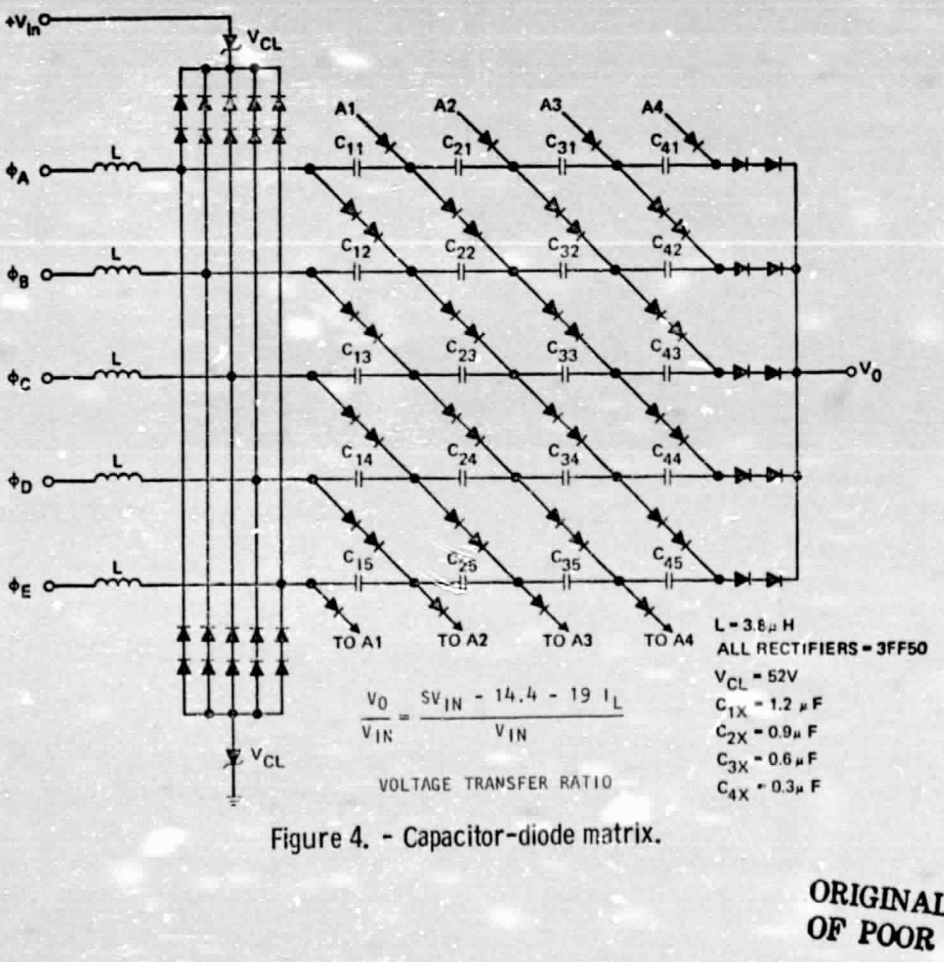


Figure 3. - Solar array V-I characteristic.



$$\frac{V_O}{V_{IN}} = \frac{5V_{IN} - 14.4 - 19\ I_L}{V_{IN}}$$

Figure 4. - Capacitor-diode matrix.

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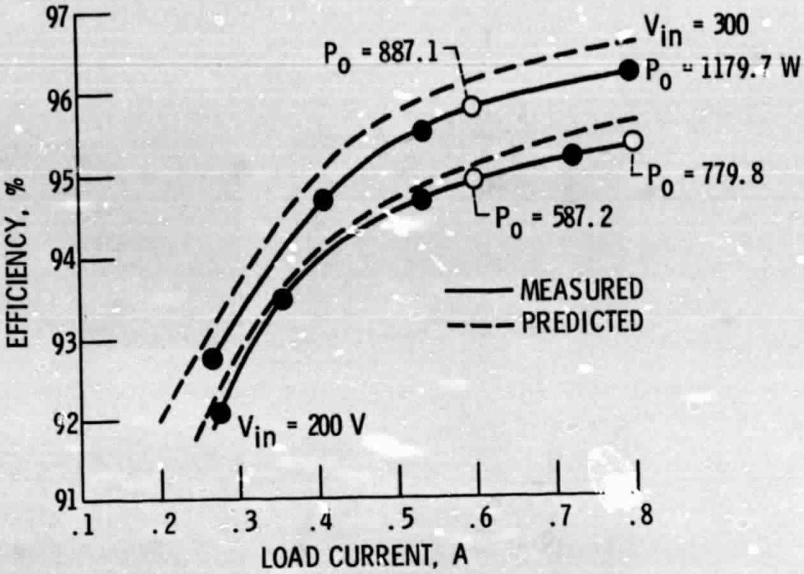

Figure 5. - Efficiency versus load current.

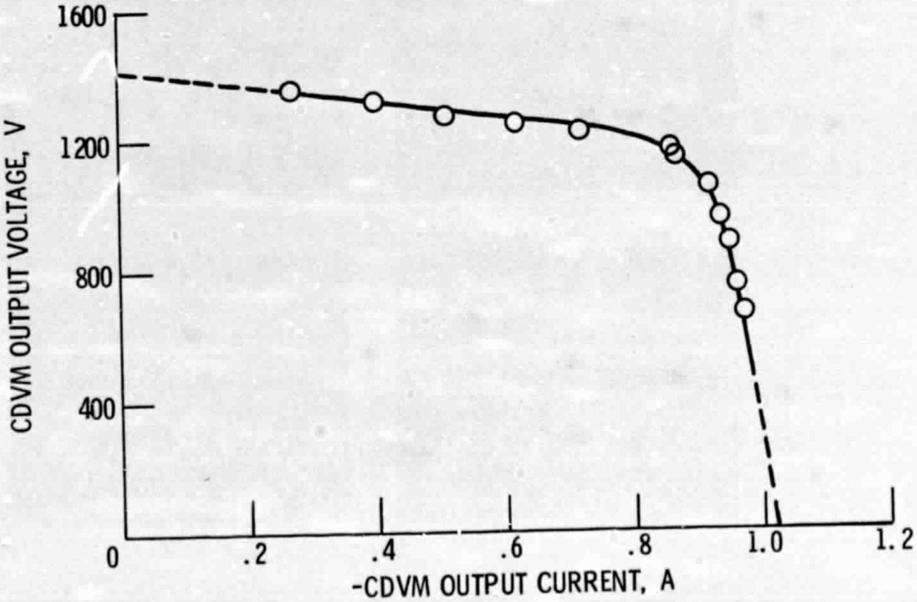

Figure 6. - S/A-CDVM V-I output characteristic.

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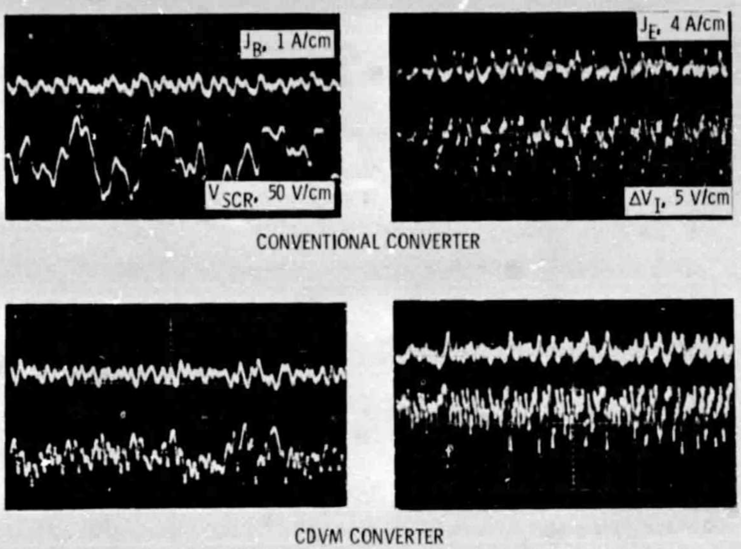


Figure 7. - Screen and discharge output waveforms: J_B = 0.6 amperes; T = 1 msec/cm.

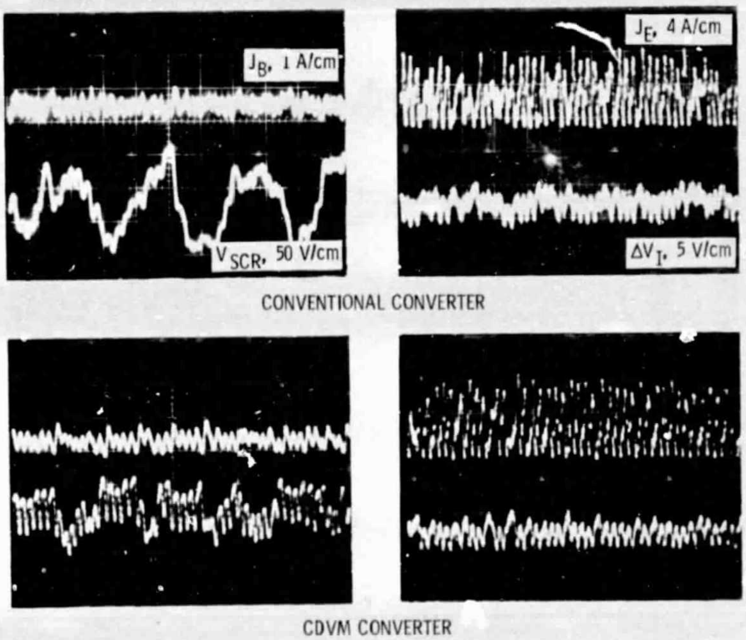
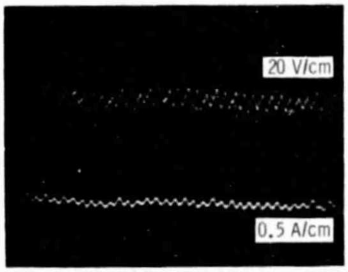
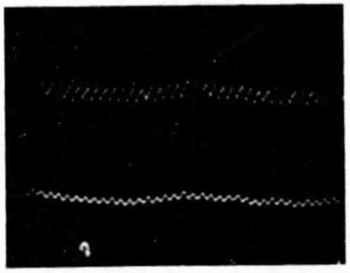


Figure 8. - Screen and discharge waveforms : J_B = 0.8 amperes: T = 1 msec/cm.

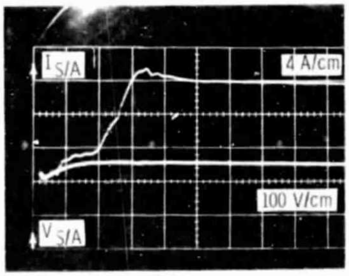


BEAM CURRENT, J_B = 0.8 A.



BEAM CURRENT, J_B = 0.9A.

Figure 9. - Solar array voltage and current ripple measurements; time = 1 msec/cm.



BEAM CURRENT, J_B = 0.9A.

Figure 10. - Solar array transient response measurements; time = 50 msec/cm.